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EXPANSIBLE SHALE RESOURCES OF THE SAN JOSE–GILROY AREA, CALIFORNIA

SPECIAL REPORT 87

California Division of Mines and Geology
Ferry Building, San Francisco
1965

THE COVER

Mt. Hamilton and the Santa Clara Valley south of San Jose. The International Business Machines Corporation plant in the middle distance is harbinger of the construction to come.

EXPANSIBLE SHALE RESOURCES OF THE SAN JOSE–GILROY AREA, CALIFORNIA

By JOHN L. BURNETT, Geologist
California Division of Mines and Geology

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CONTENTS

Page
5 Abstract
7 Introduction
8 Economic and geographic factors in the expanded shale industry
  8 Markets
  10 Property location
    10 Land use and debris control
    11 Availability of fuel
    11 Transportation facilities

11 Raw materials sources
  11 Nomenclature
  13 Geologic units
  14 Size and uniformity of the deposit
  14 Field criteria for estimating expansion properties
  15 Reactive materials

16 Physical and chemical properties
  16 Firing behavior
  22 Chemical and mineral composition
  25 Other measurements
  25 Review of the literature
  26 Discussion

29 References cited
  31 Appendix A—Sample locations
  32 Appendix B—Testing procedures used

Illustrations

Page
In pocket Plate 1 Geologic map of the San Jose-Gilroy area showing sample locations.
7 Figure 1 Location map showing the area of this study and the existing expanded shale operations in California.
8 Figure 2 Annual production of expanded shale aggregate in California.
10 Figure 3 Simplified land use map of Santa Clara County.
17 Figure 4 Heating rate of laboratory furnace.
22 Figure 5 Differential thermal analyses of shale samples.
26 Figure 6 Compositional diagram of shale samples.

Cover Mt. Hamilton and the Santa Clara Valley south of San Jose.
14 Photo 1. Freshly broken shale showing conchoidal fracture on some surfaces.
15 Photo 2. A piece of shale with conchoidal fracture developed at the center of the block.
17 Photo 3. Limestone nodule in shale of the Berryessa Formation.
17 Photo 4. Electric furnace and temperature controls used for firing the shale particles.
19 Photo 5. Expanded shale particles.
20 Photo 6. Thin sections of expanded particles from sample site K-6.

12 Table 1. Geologic summary of rock materials in the San Jose area.
16 Table 2. Chemical analyses of limestone nodules.
18 Table 3. Miscellaneous properties of the shale particles.
23 Table 4. Chemical analyses of selected shale samples.
23 Table 5. Qualitative spectrochemical analyses of shale samples.
24 Table 6. Crystalline content of shale samples by the X-ray diffraction method.

ABSTRACT

The San Jose-Gilroy area is, in many ways, an ideal site for an expanded shale industry. Positive features include a ready market and the presence of large quantities of suitable raw materials in the hills to the east of Santa Clara Valley. The principal difficulty centers on competition for the use of available land. A potential aggregate producer in this area should select his sites of operation carefully and expect some restrictions on the quarrying and manufacturing methods that he uses.

The most satisfactory sources of raw material in the area are shale beds within the older marine sedimentary units of the Berryessa Formation and equivalent rocks of Cretaceous age, the Knoxville Formation, and the Franciscan Formation. Fifteen samples were collected for laboratory study. When fired in a stationary ceramic kiln, most samples expanded within the temperature interval 2000°–2200° F. and the apparent specific gravity was reduced from about 2.5 to less than 1.00.

Bulk chemical analyses, X-ray diffraction studies, differential thermal analyses, and other analytical techniques were utilized to investigate the chemical and physical properties of the samples. The results of this study suggest that organic carbon is critical in determining the amount of expansion and that carbon dioxide is the principal gas causing expansion. The carbon dioxide probably forms from organic carbon and oxygen released during the reduction of ferric iron. The ferrous iron resulting from this reaction may act as a low temperature flux, producing a liquid phase; this would seal in the gas as it is formed, allowing expansion to take place.

EXPANSIBLE SHALE RESOURCES OF THE SAN JOSE–GILROY AREA, CALIFORNIA

By John L. Burnett

INTRODUCTION

The manufacture of lightweight concrete aggregate from common shale has been one of the most rapidly growing industries in the field of construction. Although the industry entered California in 1932, it was not until the years following World War II that expanded shale became a substantial competitor with other types of concrete aggregate. At the present time (1962) there are seven plants in California producing this aggregate (Burnett, 1960), and from 1945 to the present, the total production in California has increased by a factor of over 40 (figures 1 and 2).

Expanded shale is manufactured by rapidly heating certain types of common shale in a high temperature kiln. When the shale particles reach temperatures in the vicinity of 2000° F. to 2200° F. they partially melt, and gases which are generated within them are sealed in by the viscous glass which results from melting. The entrapped gas expands to form closed pores which enlarge the volume of the particle and decrease its apparent specific gravity. The expanded aggregate particle has a frothy, cellular interior which is surrounded by a more dense surface shell.

In California, rotary kilns are used to manufacture expanded shale, although sintering machines are commonly used in other parts of the United States. A rotary kiln, which is a long tube-like cylinder, turns at one-half to two revolutions per minute. The kiln is slightly elevated at the end where the shale is introduced and the particles move by gravity and the rotation of the kiln to the lower end, where the burner is located. In a sintering machine, the shale is placed on a continuous metal belt which moves through a stationary burning zone.

Concrete made from expanded shale aggregate combines the desirable features of low weight with high strength thus permitting it to be especially useful in concrete block, structural concrete for multi-story buildings, and a variety of specialized concrete products such as prestressed panels and beams, and storage tanks. As the cost of construction continues to rise, lightweight concrete should continue to be used in increasing quantities because of its relatively low cost in comparison to the more traditional construction materials such as wood, brick and steel.

Purpose and scope of the investigation. This study is intended to provide basic information on the economic and technical aspects of developing a commercial expansible shale industry to serve the southern San Francisco Bay area. The San Jose-Gilroy area was chosen over other localities in the state for several reasons: it is one of the most rapidly growing major urban centers in California; residential and business construction is going on at a very high rate; and it is distant enough from the nearest expanded shale supplier (figure 1) so that a plant in this area would have a local competitive advantage due to lower transportation costs. An equally important objective was to study the ceramic and mineralogical properties of a typical California shale.

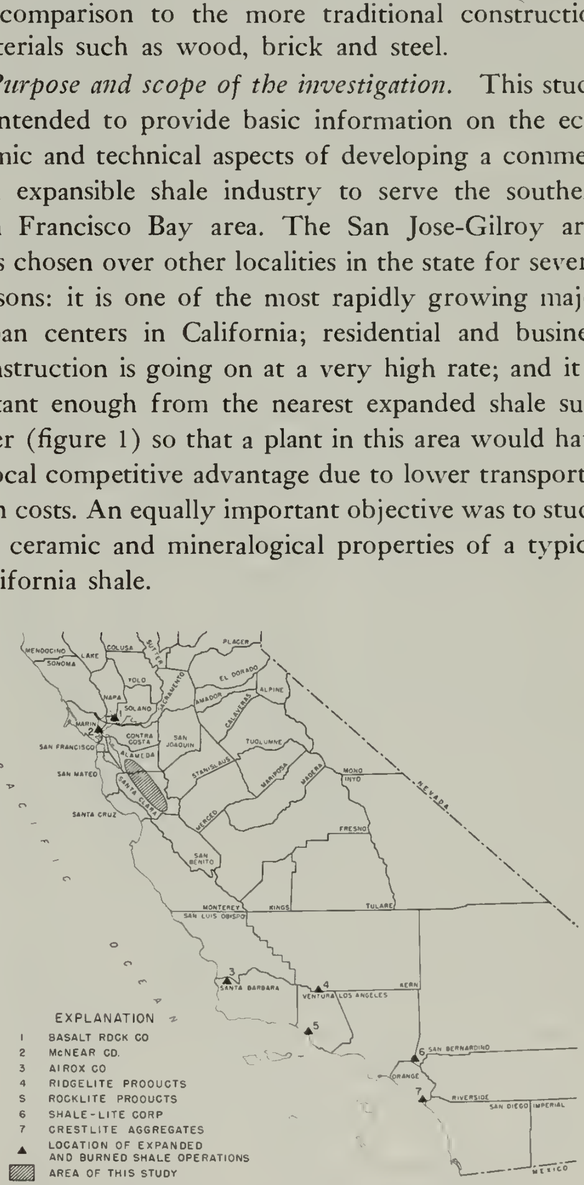


Figure 1. Location map showing the area of this study and the existing expanded shale operations in California.

The scope of the study includes two separate but related investigations. First, a survey was conducted of the economic and geographic factors that would affect a commercial operation in the San Jose-Gilroy area. The results of this work were used to define those areas of shale occurrence which are most desirable for commercial development and to exclude others. Second, samples were taken from the desirable areas and were studied in the laboratory to determine the physical and chemical properties of the shale, and their effects on expansion.

History of the investigation and acknowledgements. Field work and the laboratory testing of samples were completed by the author during 1959 and 1960. The chemical, X-ray, and differential thermal analyses were completed in 1960 and 1961. The report was written in the fall of 1961 and most of the marketing information is current as of that date although the production statistics shown on figure 2 are complete through 1962.

The author wishes to acknowledge technical assistance from a wide variety of academic, industrial, and governmental sources, especially Joseph A. Pask, R. B. Langston, and Alexander Klein of the University of California at Berkeley and Peter Kurtz, Jr. of the University of California at Los Angeles. The X-ray investigation and differential thermal analyses were done in the Ceramic Engineering Department of the University of California at Berkeley under the direction of Professor Pask. The photographs of expanded shale particles were prepared by John T. Alfors. The manuscript was greatly improved through critical reviewing which was undertaken by H. B. Goldman, F. R. Kelley, R. B. Langston, J. A. Pask and R. M. Stewart. The drafted plate and figures were completed by Richard R. Moar.

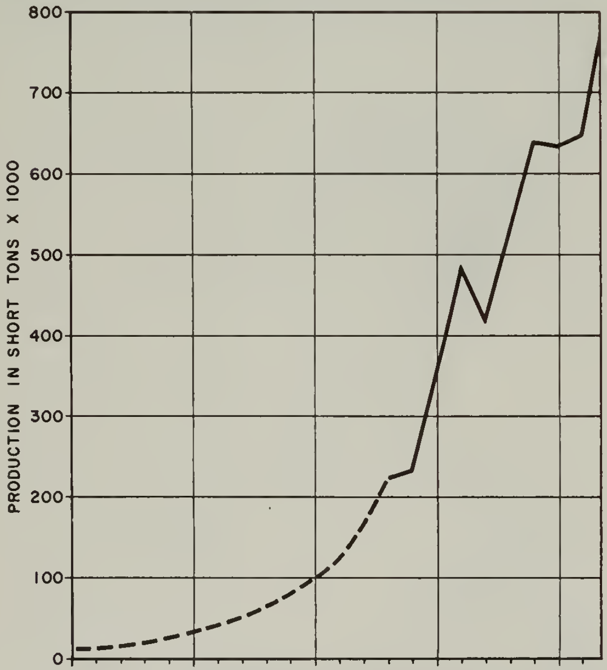


Figure 2. Annual production of expanded shale aggregate in California (the figures prior to 1953 are approximate due to incomplete statistics).

ECONOMIC AND GEOGRAPHIC FACTORS IN THE EXPANDED SHALE INDUSTRY

The mineral industry in California has long since ceased to be a business which can effectively operate solely through the energies and resourcefulness of one or two men. It has, instead, developed into a complex industry that encounters a variety of specialized problems which must be closely coordinated. In this section, some of the factors which might bear on a commercial shale expanding plant are outlined, although the reader is cautioned that specific suggestions may be of temporary value only, due to the complex changes that take place as an urban center continues to grow. The process of careful economic evaluation will, however, always be a necessary and most important step in commercial development.

Markets

Lightweight aggregate accounts for a small amount, usually around 5 percent, of the total concrete aggregate used in California construction. Within this market, however, expansible shale is by far the most commonly used type of lightweight aggregate in the San Francisco Bay Area. Concrete block producers are the largest consumers of lightweight aggregate, and lightweight concrete for monolithic (or poured in place) construction is the second most important use. About 5 percent of total expanded shale production is consumed for use in prestressed concrete, storage tanks and other manufactured products, and roofing granules.

Expanded shale is used in concrete to reduce the total weight of the structure. In multi-story building construction this reduced weight may permit: the use of smaller quantities of structural steel; a reduction in the number and complexity of the supporting members; and advantages in design flexibility, such as longer spans between columns and the use of cantilever construction. The decision to use lightweight concrete in large buildings also depends upon other factors. A reduction of the total weight of the structure becomes important when buildings reach a height of about nine stories, when the building foundation rests on piles, or when an earthquake problem exists. Lightweight concrete is used extensively for the manufacture of concrete block due to the lower cost of handling and transporting the finished product. Another factor is that labor union regulations, in some areas, restrict the maximum weight of a concrete block that can be handled by one man, thus encouraging the use of lightweight aggregate. Although lightweight concrete is more expensive than concrete using common sand and gravel, the above mentioned factors often serve to reduce the total cost of construction.

There are several reasons for the limited use of lightweight aggregate in comparison to common aggregate. Expense is the greatest factor. Expanded shale costs three to four times as much as sand and gravel, and the prepared lightweight concrete is nearly twice as expensive. Also, concrete block, which is made from lightweight aggregate almost exclusively in northern California, plays a relatively minor role in northern California residential construction because lumber is more widely used. Other reasons include the additional facilities and costs which are required in handling and mixing a separate type of aggregate.

The potential market for expanded shale in the southern San Francisco Bay area appears to be promising because this area is one of the most rapidly growing population centers in California. In the past ten years, residential and light industrial building has nearly filled the area to the northwest from San Jose to Palo Alto. At the present time, residential building is very active in the undeveloped area to the north between Hayward and San Jose. Future building expansion is expected to the south toward Gilroy although it may be several years before this trend is realized on a large scale. For the purposes of this study, it was assumed that all of this building activity offers a market which is adequate to justify establishing an expanded shale industry in the area.

The lightweight aggregate industry is a highly competitive one which is able to make a profit only through sales in high volume at competitive prices. California has an unlimited supply of raw materials suitable for expanded shale production, and there are many satisfactory products presently on the market. Any new expanded shale operation must, therefore, be designed to operate at the maximum possible efficiency, and the new product must offer some advantage over competing ones which are now in use. The most important advantage that a producer in the San Jose area could offer is a lower cost of the delivered aggregate due to the shorter haul distance to local construction sites. For this reason, the quarry and processing plant should be located as near as possible into a major center of building such as San Jose. Highway and railroad transportation facilities are available on Highway 101 and the Southern Pacific Railroad between San Jose and Gilroy.

An expanding plant might be planned in several ways: An operation could be designed only to mine and process the shale with the finished aggregate being sold on the open market; or a completely integrated operation could be established which would include mining, expanding and the manufacture of finished concrete products, primarily concrete block. The fully integrated operation offers the best opportunity for maximum capital return, but there would be advantages in initially confining the operation to aggregate manufacture:

1. The initial investment would be kept small until the aggregate manufacture could be perfected. It may require months or even years of experimental plant operation to develop the best handling methods and kiln adjustments.

2. It would take some time for the aggregate itself to be tested in use to the point where it would be acceptable as a substitute for presently available expanded shale.

3. Sale of the aggregate on the open market would be more successful if the aggregate manufacturer does not produce finished blocks. Independent block manufacturers are reluctant to purchase aggregate from a company which competes with them on the concrete block market.

Another aspect of the competitive situation in lightweight aggregate is competition from materials other than expanded shale. Pumice and volcanic cinder have been used extensively in the past, but they are being replaced by more expensive expanded shale despite its higher cost because of its lower water absorption, higher strength and greater resistance to breakage during handling. In many construction jobs, the contractor is required by architectural specifications to use expanded shale of a type that is equal or superior in quality to one of the presently available products, thereby excluding both pumice and volcanic cinder. The principal advantage of pumice and volcanic cinder lies in their lower price at the source, but these are far enough away so that transportation costs tend to limit this advantage.

A competitive threat to expanded shale may lie in the future development of concrete aggregate from furnace slag in the Bay Area. At the present time, moderate quantities of slag are being produced by the open hearth method from a steel plant at Niles, Alameda County but this material could not readily be utilized for the production of lightweight aggregate due to its high specific gravity. If a fully integrated steel industry were established somewhere in the San Francisco Bay Area, blast furnaces probably would be used and the slag produced might be lower in density than that produced by the open hearth

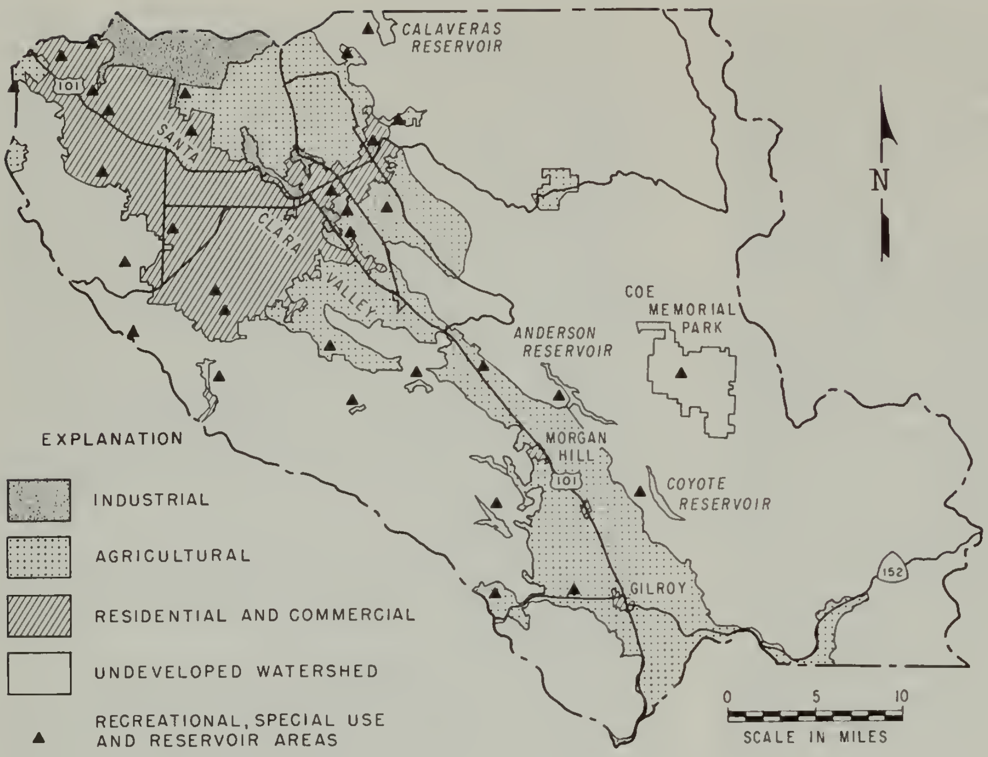


Figure 3. Simplified land use map of Santa Clara County.

method. The slag output from such a plant possibly could supply a large portion of the demand for lightweight aggregate in this area, and slag would have the economic advantage of being a waste product which could be sold with a very small profit margin. In the eastern United States, lightweight aggregate produced from slag has for many years been used in concrete block and structural concrete.

Property Location

The location of the various facilities of an expansible shale operation greatly affects the economy and efficiency with which the operation is able to serve its intended market. In addition to a nearby source of raw materials, consideration must be given to land use, debris control, availability of fuel, and transportation facilities when choosing sites for the quarry and processing plant.

Land Use and Debris Control

The rapid growth of population in the San Jose area has created a highly competitive situation for the use of available land. The requirements of residential, recreational, and industrial uses of land are commonly opposed to one another, and it is the function of a planning agency to recommend the best solution in these disputes for the general benefit of the community. The planning agency is usually consulted by the Board of Supervisors on the advisability of all industrial and quarry operations within the county. Although the conclusions of this agency are not binding upon the Board, they are seldom ignored. The extreme complexity of these decisions is suggested by the points which are discussed below.

Santa Clara County has a high living standard which is based on agriculture and defense industries, primarily research and development of aircraft and electronic products. These industries are desirable industrial operations because they do not create excessive dust, smoke, noise, or defacement of scenery and therefore are not objectionable to nearby residential and recreational areas. Owing to this situation, business and governmental groups in Santa Clara County are not encouraging industrial plants which might be objectionable to locate in this area, although they would be permitted if certain restrictions on their operation were observed. An expanded shale operation would be considered as moderate to heavy industrial use, because a certain amount of dust is inherent in the quarrying and handling of shale.

The present use of land in Santa Clara County is summarized on Figure 3. In general, industrial plants are encouraged to locate on the tidal areas at the northern end of the county or along U.S. Highway 101, which lies along the center of Santa Clara Valley. The undeveloped watershed areas, where the known shale deposits are found, are also available for industrial development, although the recreation and reservoir areas should be avoided.

Air pollution is of great concern throughout California, especially in areas such as San Jose where industrialized valley regions are surrounded by hills which tend to prevent the dissipation of debris in the atmosphere. A shale quarry and expanding plant are both potential sources of debris and therefore an operator would be required to take measures to prevent air pollution. Dust would have to be controlled so that it would not drift into other occupied areas near the shale quarry or expanding plant. The waste products of an expanding kiln which are released into the atmosphere consist of smoke, water vapor, carbon dioxide and small quantities of sulfur dioxide. Smoke can nearly be eliminated by using natural gas as fuel and the remaining gases should not create a problem.

Wind-carried dust could also be a source of contamination of the water storage reservoirs which are maintained in the area. Anderson Reservoir and Coyote Reservoir are used as ground water recharge basins. A portion of their contained water percolates into permeable sedimentary rocks which bound the lakes on the western side. This water eventually migrates westward to replenish water removed by wells in the Santa Clara Valley. The percolation could be reduced if fine-grained material, such as silt or clay, were drawn into the pore spaces of the sedimentary rock from the lake water. Calaveras Reservoir is a storage facility for the San Francisco public water supply. If a quarry or expanding plant were located near any of these reservoirs, adequate dust control measures would be required to prevent dust from being carried into the reservoirs by wind or tributary streams.

Several areas on the eastern side of Santa Clara Valley are, or will be, used for recreational purposes. Anderson Reservoir and Coyote Reservoir are presently being developed as summer home and water sport areas, and Coe Memorial Park is an undeveloped area several miles east of Anderson Reservoir which will be developed at some future date. The agencies which administer these areas might require that quarry workings and plant facilities be located so that scenery would not be defaced within sight of the recreation areas.

Availability of Fuel

The expansion of shale requires large quantities of fuel for heating the kilns. The most inexpensive source of fuel in the vicinity is a major natural gas trunk line which lies along the eastern side of Santa Clara Valley.

Industrial plants normally purchase natural gas at a low cost on a schedule known as interruptible service. The price advantage virtually requires that an industrial customer use this type of service, but he must provide emergency fuel reserves, usually fuel oil, in case of an actual or threatened shortage of natural gas, and he normally must pay the cost of constructing a pipeline from the trunk line to his plant.

Transportation Facilities

The cost of transportation is critical in a large volume, low cost material such as expansible shale; therefore, the plant facilities should be located as near as possible to a major sales area such as San Jose. A line of the Southern Pacific Railroad connects Gilroy and San Jose which could be used for shipments to other parts of the state.

Although of less importance, the cost of transporting and handling the material between quarry, processing plant, and final point of loading into truck or railroad car must also be considered. Normally the least expensive means of handling quarry material is to place the quarry and processing plant close together so that the quarrying equipment can also deliver the raw material to the plant stockpile. In the San Jose area, several factors combine to prevent this ideal situation. Land use and debris control restrictions tend to limit operations in the vicinity of the shale deposits to an absolute minimum. Quarrying would have to be done here but it would be more desirable to locate the processing plant in an area which is zoned for heavy industrial use.

The shale deposits are located a number of miles from the railroad and natural gas pipeline. If a processing plant were located near these facilities, the cost of railroad spur lines and natural gas service lines could be greatly reduced.

RAW MATERIALS SOURCES

Nomenclature

Expansible shale, or bloating shale as it is commonly called, is the term for a potentially commercial mineral raw material. In this regard, the term refers as much to the manufacturing process involved as it does to the raw material. The term "shale" is used in the broadest possible sense and includes such lithologic types as clay, mudstone, and slate.

Almost any rock which is rich in clay-sized particles could be expanded by heating if the raw material were specially treated or if a very lightweight product were not required. Shale which has no natural tendency to expand can be utilized if the shale is first ground and pelletized with the addition of materials which will cause expansion although this method would greatly increase the expense of processing. Some shale will not expand until excessively

Table 1.—Geologic summary of rock materials in the San Jose area.

Geologic unit	Geologic age and origin	Lithologic character	Remarks
SEDIMENTARY AND METASEDIMENTARY ROCKS			
Alluvium	Recent non-marine sedimentary rock	Unconsolidated gravel, sand and clay	Deposits of clay typically are variable in size and composition. Moderately uniform deposits are known in Santa Clara Valley. The included clay could be used for expansion but expensive beneficiation techniques would be necessary to separate the clay from coarser material.
Santa Clara Formation and related rock units	Plio-Pleistocene non-marine sedimentary rock	Poorly sorted, poorly indurated gravel, sand and clay with minor marl, siltstone, mudstone and tuff	Clay deposits are individually small and display extreme lateral variation. The included clay could be utilized for expansion but expensive beneficiation techniques would be necessary to separate the clay from coarser material.
Purisima Formation	Mio-Pliocene marine sedimentary rock	Conglomerate, sandstone and poorly indurated shale	Quantity of available shale appears to be too small for commercial development.
Orinda Formation	Mio-Pliocene non-marine sedimentary rock	Conglomerate, sandstone, silt and clay with minor andesite tuff	Quantity of available clay appears to be too small for commercial development.
Briones Formation	Miocene marine sedimentary rock	Calcareous pebble conglomerate and sandstone	Material is not suitable for expansion.
Monterey Group (includes the Sobrante Sandstone, Claremont Shale, and Oursan Sandstone	Miocene marine sedimentary rock	Sandstone, siltstone, siliceous shale and chert with minor lenses of calcareous shale and impure limestone	Material does not appear to be suitable for expansion.
Vaqueros Formation	Miocene marine sedimentary rock	Sandstone and conglomerate with minor diatomaceous to clay-rich shale	Quantity of suitable shale appears to be too small for commercial development.
San Lorenzo Formation	Oligocene marine sedimentary rock	Poorly indurated clay shale with interbedded fine-grained sandstone	Shale could be utilized but its lack of induration might require pelletizing before expansion. The only known outcrops of this material are undesirable because of land use restrictions.
Unnamed rocks	Eocene (and/or Paleocene) sedimentary rocks	Calcareous shale with some sandstone. Some limestone nodules are present. These rocks are lithologically similar to the Berryessa Formation but are distinguished on the basis of fossil evidence	Largest known occurrences are west and northwest of Morgan Hill. Unit varies in stratigraphic thickness from ±400 feet on the south to over 3,500 feet to the north. Individual shale beds are 75 to 400 feet thick. Shale can be utilized for expansion but calcareous material may require special treatment.
Berryessa Formation (includes the Niles Canyon Formation of Hall and undifferentiated Cretaceous rocks)	Cretaceous marine sedimentary rock	Sandstone, shale and siltstone. Limestone nodules and thin, silty limestone beds are found in the shale. Conglomerate lenses are common. Shale is most common toward the base of the formation which is adjacent to the Calaveras fault in much of the area. The shale is well indurated, black to olive green in color and displays prominent conchoidal fractures on weathered surfaces	Total thickness of the unit is unknown but it exceeds 3,000 feet. The shale beds grade laterally into coarser material but many individual shale deposits are 50 to 100 feet in thickness and have considerable lateral extent. All shale within this unit is very uniform in composition. Shale can be utilized for expansion but calcareous material may require special treatment.
Oakland Conglomerate	Lower Cretaceous marine sedimentary rock	Cobble and boulder conglomerate	Material is not suitable for expansion.

Table 1. Geologic summary of rock materials in the San Jose area.—Continued

Geologic unit	Geologic age and origin	Lithologic character	Remarks
Franciscan Formation	Cretaceous-Jurassic marine sedimentary and metasedimentary rocks	Sandstone, shale, siltstone and conglomerate with minor chert and schist. Shale is very well indurated; olive grey to black in color; commonly displays a slaty cleavage and is highly contorted from structural deformation.	The thickness of the formation is great but not precisely known. The thickness and lateral extent of individual shale beds is difficult to determine due to deformation. Exposures of uniform shale are generally small except in the isolated north-eastern portion of the Santa Clara County. If slaty cleavage is not developed the shale closely resembles shale of the Knoxville and Berryessa Formations. The shale can be utilized for expansion but large, uniform deposits are not readily accessible.
Knoxville Formation	Jurassic marine sedimentary rock	Shale, siltstone and some feldspathic sandstone. Lenticular limestone beds and limestone nodules are occasionally present. The shale is well indurated, thin-bedded, dark grey to black in color and displays slightly developed slaty cleavage in some areas. Conchoidal fracturing is often evident on the weathered outcropping	The thickness of the formation is great but not precisely known. Geologic structure within the unit is difficult to determine due to deformation and lack of marker beds. The shale can readily be utilized for expansion.
IGNEOUS ROCKS			
Younger volcanic rocks	Tertiary and Quaternary extrusive and shallow intrusive igneous rocks	Andesitic tuff and basalt flows within the Orinda Formation, Santa Clara Formation and related rock units. All known units are thin and discontinuous	Material is not suitable for expansion.
Older intrusive and extrusive rock within the Franciscan Formation	Cretaceous (?) intrusive and extrusive rocks of basic to ultrabasic composition	Basalt, diabase, gabbro, greenstone and serpentine	Material is not suitable for expansion.

high temperatures are reached and, although the product may be satisfactory, the cost of the required fuel may be prohibitive. Under the present state of technology, materials which expand at temperatures above 2300° F. are considered to be uneconomic; those which expand below 2100° F. are most desirable. A non-expanding shale can be furnaced to produce very strong, unexpanded aggregate; its weight would be greater than true expanded shale although less than common sand and gravel aggregate.

All of these possibilities either increase the cost of production or decrease the quality of the product and for the purposes of this investigation, it seemed desirable to ignore materials with these deficiencies. The present study is concerned only with those materials that display a natural tendency to expand within an economically feasible temperature range and the term "expansible shale" will be restricted to this meaning. The basic requirements of size graduation and weight for expanded shale are stated in the American Society for Testing materials specification for lightweight aggregate (A.S.T.M. designations C 331-59T and C 330-60T).

Geologic Units

The rocks in the San Jose-Gilroy area range in age from Jurassic to Recent and include a variety of lithologic types (table 1); these rocks have been described by Branner, Newsom and Arnold (1909), Crittenden (1951), Frames (1955), Hall (1958), and Ortalda (1950).

Shale and clay are similar types of rock, both of which contain large quantities of very fine-grained material, known as the clay-size fraction. Clay-rich rocks are found in many of the geologic units but large quantities of uniform, clay-rich material are found only in the older marine sedimentary units—the Knoxville, Franciscan and Berryessa Formations—and within the younger (Oligocene) San Lorenzo Formation. Most of the shale within these units is suitable for the manufacture of lightweight aggregate for concrete. The San Lorenzo Formation was not studied because it is exposed only in an area which is being developed for residential purposes, where land use restrictions would severely limit or prohibit an industrial operation.

Shale tends to disintegrate readily during the process of weathering and its surface exposures are subject to slumping and landsliding. Areas which are underlain by shale are normally covered with vegetation and soil; outcrops of the undisturbed shale are rare unless the rock has been artificially exposed such as in a roadcut. For this reason, much more shale may be present than is indicated by the number of sample sites shown on plate 1. An accurate estimate of the shale reserves in this area cannot be made but the volume present is probably best described in terms of cubic miles of material. Bulldozer trenching or drilling would be necessary to appraise the covered areas; therefore, the sample sites on plate 1 should not be regarded as shale deposits but rather as isolated "windows" in this pervasive cover where the underlying rock is exposed.

Size and Uniformity of the Deposit

Commercial development of an expansible shale deposit requires that it be as large and uniform as possible. Sedimentary rocks such as sandstone, siltstone and conglomerate are coarser in grain size than shale and they will not expand under any conditions. If these rocks are processed with the shale, they will increase the average weight of the finished aggregate thereby reducing its most useful characteristic. In the area of this study, sandstone and siltstone are commonly interbedded with shale, but careful exploration will reveal local areas which contain large, fairly uniform deposits of shale. Large quantities of relatively pure shale are present in the Knoxville Formation, and many beds of shale 50 to 100 feet thick are found in the Berryessa Formation. The readily accessible outcrops of the Franciscan Formation are known to contain only small, impure deposits of shale, although large quantities of uniform material are exposed along San Antonio Road in a remote area approximately 10 miles east of Mt. Hamilton. Most of the samples were taken from areas which contain large quantities of shale and which should supply ample reserves for a commercial operation. Exceptions to this are sample numbers K-15 and KJ-2; these were collected from shale bodies which are known to be small.

Before a deposit is developed it should be thoroughly explored by a systematic drilling campaign in order to establish that sufficient shale is present to supply a commercial operation. The results of this drilling would also be an important guide for the planning of mining methods.

Field Criteria for Estimating Expansion Properties

The only means of accurately appraising the expansibility of a shale sample is to test the material in a ceramic kiln. There are, however, several characteristics of the shale in this area which have been useful in estimating the expansion properties of a particular sample (Burnett 1964).

In the samples of shale which were collected for this study, expansibility is associated with the color of the shale. Samples in which shades of black and dark green predominate tend to expand the most. These colors usually indicate the presence of organic carbon and ferrous iron respectively (Weller 1960); both of these constituents are reducing agents that tend to be oxidized and therefore removed during weathering. When the shale is weathered, shades of brown, yellow and red tend to predominate, indicating the presence of iron in the ferric state of oxidation and expansion is reduced or eliminated. The ferric iron is present as a variety of hydrous iron oxides (limonite) that have been derived by oxidation of the ferrous iron originally present in the shale. Therefore, samples which are collected for testing should be taken from sites which have sustained as little weathering as possible (White 1959). Most surface samples have suffered some weathering, but the effect of weathering can be minimized by collecting samples from excavations, such as road cuts.

Photo 1. Freshly broken shale showing conchoidal fracture on some surfaces. The appearance of these pieces is typical of the shale found in the Berryessa Formation.

The color differences between samples which expand well, poorly or not at all are subtle and difficult to describe, but these differences can be detected when one gains experience. Color is best used to estimate the differences in expansibility of shale within a particular geologic unit, because the shale from one formation will usually have a characteristic color in the unweathered state. Variations from this color can be detected by comparison with a fresh sample.

Grain size is another factor of importance because expansibility is greatest in rocks which are composed of clay-sized particles. A rock composed of silt-sized particles normally will not expand, although expansion will take place if the rock contains a mixture of particles in the silt and clay sizes. The conchoidal fracturing that is characteristically developed in shale of the Berryessa and Knoxville Formations appears to reflect the presence of clay sized particles and is a dependable means of distinguishing clay shale from silty shale (photo 1 and 2).

Shale can generally be distinguished from fine-grained rocks of non-sedimentary origin by differences in color and texture. In cases of doubt, the unweathered rock can be tested with a knife blade; shale is readily scratched by the blade whereas fine-grained igneous and metamorphic rocks are not.

Slaty cleavage is common in shale from the Franciscan Formation and is often present in shale from the Knoxville Formation. Slaty cleavage is caused by the parallel orientation of the constituent clay particles (Bates, 1947) in response to deformation. During furnacing, expansion takes place in only one direction; that is, perpendicular to the basal cleavage plane of the clay particle. If clay particles are oriented with most of their cleavage planes parallel to one another, the rock will only expand perpendicular to that plane. The resulting expanded particle is flat on two opposite sides and has accordion-like pleats on the other sides. Shale from the Berryessa Formation displays little or no tendency toward slaty cleavage and, presumably, its clay particles are not well oriented. The expanded shale from this formation tends to be round and equidimensional.

Photo 2. A piece of shale with conchoidal fracture developed at the center of the block.

Reactive Materials

In recent years, considerable attention has been given to reactive materials in aggregate which can cause failure of the concrete in which such aggregate is used. Failure of this type is most commonly the result of chemical reactions, involving an increase in volume of some part of the aggregate, which take place after the concrete has hardened. The increased volume creates internal stresses which can cause cracking of the concrete although complete structural failure seldom, if ever, takes place.

The shale samples which were investigated in this study contain several constituents which have been known to react unfavorably in concrete. Organic carbon and pyrite are present and are potentially reactive in normal aggregate, but the intense heat of the expanding kiln destroys the reactive properties of these constituents. Limestone is not reactive in normal aggregate, but during the heating process, it would be converted to calcium oxide or "quick lime", which would react with water in the concrete mix to form calcium hydroxide.

There is no known record of complete failure in a concrete structure due to calcium oxide in the aggregate but minor spalling at the surface of the concrete ("popouts") is commonly traced to this cause. The pits left by the spalling are unsightly and steps should be taken to eliminate calcium oxide as a possible source of reactivity. Small particles of calcium oxide would not be troublesome because they would hydrate before the concrete could harden, but large pieces would react more slowly and cause trouble. Any magnesium oxide which was present as original dolomite, could be troublesome because it reacts with water more slowly than calcium oxide.

Nodules and lenticular beds of magnesian limestone are common in the Berryessa Formation and are occasionally seen in the Knoxville Formation (photo 3). Four samples of these nodules were collected from the Berryessa Formation for analysis; three (nodule samples 1, 2 and 3) were found out of place southeast of Coyote Reservoir; and one (nodule sample 4) is from shale sample site K-17 which is northwest of Calaveras Reservoir. The chemical composition of these samples is presented on table 2. The magnesia content of the samples is low, although sample 4 has a relatively higher content than the others. Six size fractions, ranging from ½″ to 60 mesh, of each sample were furnaced to a maximum temperature of 2300° F. Samples 1, 2 and 3 became almost completely soluble in water, indicating that most of the limestone was converted to calcium oxide. Sample 4 fused completely, probably because its large content of acid insoluble

Table 2. Chemical analyses of limestone nodules.
G. W. Martin and Lydia Lofgren, Analysts (Dec. 1, 1961)

In percent

	Nodule no. 1	Nodule no. 2	Nodule no. 3	Nodule no. 4
Acid Insoluble	11.21	14.98	11.73	35.26
CaO	47.35	45.00	46.62	30.12
MgO	1.02	0.90	1.28	1.79
CaO/MgO	47.3	50.0	36.4	16.8
CaO and MgO calculated as carbonates				
Acid Insoluble	11.21	14.98	11.73	35.26
$CaCO_3$	84.55	80.35	83.25	53.80
$MgCO_3$	1.39	1.90	2.69	3.76
TOTAL	97.15	97.23	97.67	92.82

material contained enough clay to lower the melting point of the rock.

Limestone should be avoided if possible. If it cannot be avoided through selective mining, it may be handled in other ways. The nodules commonly are six inches or larger in size, very difficult to break, and they might be removed as oversize after the first stage of crushing. As a final safeguard against reactivity, the finished aggregate could be soaked in water after furnacing to hydrate any calcium oxide which was present. This last procedure has been successfully applied by at least one California producer of expansible shale.

PHYSICAL AND CHEMICAL PROPERTIES

The expansion of shale is controlled by a complex combination of factors which depend upon the physical and chemical properties of the shale. The shale particles expand when they reach the temperature where melting has just begun. At this point, any gases which are generated within the particle will be sealed in by the viscous glass which results from melting, and the gas will expand to form closed pores within the particle. The expansion will continue with increasing temperature until the glass becomes so fluid that it will allow the gas to escape. A necessary prerequisite for expansion is that fusion and gas formation must take place at the same time within the particle.

A total of fifteen samples was collected for study from locations which are plotted on plate 1 and described in Appendix A. Most of the samples were collected from geographically desirable areas, as discussed above, which have enough shale present to be of commercial interest. Care was taken to collect material which had sustained as little weathering as possible. Roadcuts and other recent excavations were the preferred sample sites, although surface material was collected where excavations could not be found.

The geologic age and formational unit of each sample is indicated by the letter prefix of the sample number. Samples with numbers beginning with "K" were collected from the Cretaceous Berryessa Formation and its equivalents. The letter "J" denotes the Jurassic Knoxville Formation and "KJ" denotes the Franciscan Formation of Cretaceous or Jurassic age.

In collecting the samples, as much weathered surface material as possible was removed, and approximately fifteen pounds of shale was taken from a channel 1 foot to 3 feet long, cut at right angles to th plane of bedding. The samples were stored for severa months in paper bags at room temperature befor the testing procedures were started. This method o storage and the time lapse between sample collectio and testing would cause some of the contained moisture to be lost but this should not have greatly affecte the test results.

Firing Behavior

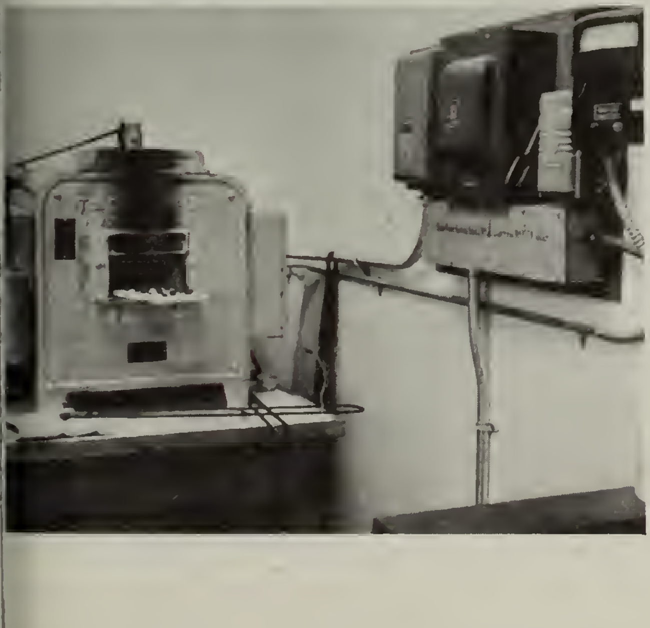
The testing procedures for expansible shale ra materials are not well standarized, but furnacing i normally used as the basic test of expansibility. Th procedures used in this study were standardize within the investigation so that results between individual samples could be directly compared. Th ideal expanding conditions for an individual sampl were not determined because, in a commercial operation, this would depend, in large part, upon th specific procedures and equipment used.

Photo 3. Limestone nodule in shale of the Berryesso Formation. The nodule (below the point of the pick) is elliptical in shape and lies in the plane of the bedding.

All of the furnace testing was done using particles of the shale which were crushed and sized to an average diameter of one-half inch. The furnace used is a one-eighth cubic foot stationary electric kiln equipped with four globar heating elements and an automatic temperature control (photo 4). No attempt was made to control the furnace atmosphere, and therefore the testing was done under oxidizing conditions.

Each sample was tested in two standardized firing procedures. In the first procedure, ten of the half inch particles of shale were placed on a clay plate in the furnace at 1000° F., and the furnace temperature was increased at its maximum rate (Figure 4). Between 1850° F. and 2300° F., one particle was removed from the furnace at each 50° F. increase in temperature. The resulting suite of fired particles demonstrates the progression of expansion between these temperatures. This suite was also used to determine the temperature of maximum expansion and the temperature at which the surface of the particle begins to melt and become sticky. Spalling or explosion of the heated particle was detected by the sharp "popping" sound that results when this takes place in the kiln.

Photo 4. Electric furnace and temperature controls used for firing the shale particles.



In the second procedure, approximately 30 pieces of one-half inch sized shale were heated again at the maximum rate, from 1000° F. to the temperature of maximum expansion, as determined from the first procedure. The aggregate produced in this second test was used to measure the apparent specific gravity and water absorption of the fired aggregate (table 3).

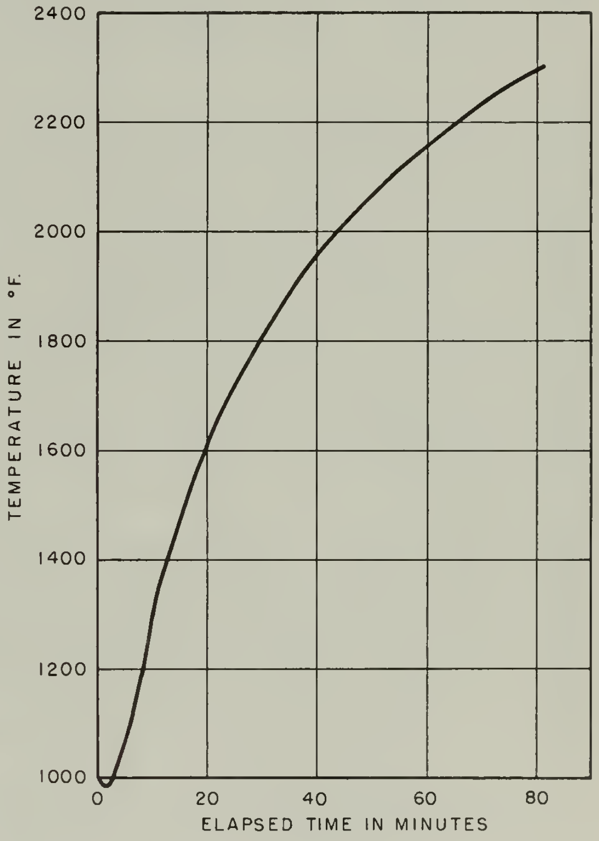


Figure 4. Heating rate of laboratory furnace.

The samples were cooled by removing them from the kiln. In order to reduce spalling, which is primarily caused by moisture in the shale, all samples were preheated at 300° F. for 30 to 40 minutes before being placed in the expanding furnace.

The time-temperature conditions of these tests approximate those in a commercial expanding kiln. For example, the feed end of most commercial kilns is maintained at 1000° F. to 1200° F., and the time during which the shale is retained in the kiln ranges from 30 to 75 minutes. The preheating of samples approximates the conditions which are established

*Table 3. Miscellaneous properties * of the shale particles.*

Sample number	Properties of the crude shale			Expansion characteristics				Properties of the fired aggregate				
	Apparent specific gravity	pH	Reducing power[1]	Expansion range in °F.	Temperature of sticking in °F.	Optimum expansion temperature in °F.	Spalling	Particle shape	Fired color	Apparent specific gravity	Water absorption in weight percent	Apparent specific gravity ratio[2]
K-6	2.69	9.14	0.56	2000–2200	2250—slight	2200	Some at 1000°F.	Round	Brick red	.87	8.64	3.08
K-7	2.57	9.13	0.56	1950–2150	2200—slight 2250—moderate	2150	Considerable at 1000°F.	Round	Brick red	.67	5.78	3.82
K-8	2.28	6.16	0.56	2100–2275	2250—slight	2200	Considerable at 1100°F.	Round	Pale buff	.70	7.34	3.26
K-9	2.52	6.77	0.39	2000–2200	2300—slight	2180	Some below 1850°F.	Round	Brick red	1.25	5.65	2.02
K-10	2.63	6.97	0.34	1950–2150	2250—slight	2150	None	Round	Brick red	.95	5.85	2.78
K-11	2.58	6.84	0.37	1950–2150	2250—slight 2300—moderate	2150	None	Round	Brock red	.69	5.09	3.73
K-12	2.59	6.93	0.29	2000–2125	2150—slight 2200—moderate 2250—severe	2125	None	Round	Brick red	.80	3.35	3.23
K-13	2.55	7.61	0.41	1950–2050	2150—slight 2250—moderate	2050	None	Round	Brick red	.87	6.03	2.94
K-14	2.36	6.82	0.52	2000–2300	2300—slight	2280	None	Round	Brick red	1.23	1.35	1.93
K-15	2.20	5.18	1.12	2100–2300	2250—slight 2300—moderate	----	None	Round	Pale buff	1.61	2.49	1.37
K-16	2.51	6.94	0.64	1950–2125	None noted	2100	Some at 1000°F.	Round	Brick red	.97	8.20	2.60
K-17	2.50	7.19	0.70	1950–2150	2200—moderate 2250—severe	2130	None	Round	Brick red	.94	2.30	2.67
J-2	2.49	7.41	0.66	1950–2100	2150—slight 2200—moderate 2250—severe	2060	None	Accordian	Brick red	.89	10.59	2.82
J-3	2.36	6.64	0.27	2000–2200	None noted	2200	None	Round	Brick red	1.49	1.46	1.57
KJ-2	2.63	7.20	0.61	2050–2100	2200—moderate 2250—severe	2070	None	Accordian	Brick red	1.35	7.90	1.95

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* A complete discussion of the methods used is presented in the text.

[1] Reported in ml. of 0.1 N $K_2Cr_2O_7$.

[2] $\frac{\text{Apparent specific gravity of the crude shale.}}{\text{Apparent specific gravity of the fired aggregate.}}$

y the drying stage of a commercial plant. The quipment used in these tests does not, however, dupliate all of the conditions found in a commercial plant. The gases present in the atmosphere of the elecric furnace are different from those found in a gasired kiln, and the maximum heating rate of the laboraory furnace is less than the rate of heating in some ommercial kilns. Furthermore the mechanical abraon that takes place when the shale moves through a otary kiln is not duplicated in a stationary furnace. or these reasons, a commercial operation would not ecessarily duplicate the results of this study but, in e writer's opinion, commercial expansion of the aterial represented by these samples would produce e same relative differences which are reported here.

The ratio of the apparent specific gravity * of the rude shale to that of the fired aggregate is used as measure of expansion, but it must be remembered at this ratio reflects both volume increase and eight loss due to the removal of volatile constitunts in the shale. A shale sample which fires with no bservable volume increase whatsoever will comonly have an apparent specific gravity ratio of aproximately 1.3 due to removal of water and other olatiles. Approximately two-thirds of the samples escribed on table 3 are capable of being expanded the point where they will float in water (apparnt specific gravity of less than 1.00). Although an xtremely low apparent specific gravity is not reuired in many aggregate uses, it is desirable in me. The amount of expansion can easily be rerded by operating at a kiln temperature below that hich produces maximum expansion. If the raw marial is capable of being expanded to very light eights, the producer is able to manufacture aggrete of differing weights to fit various specifications.

The expansion range on table 3 was determined by sual inspection of the first firing procedure. The wer temperature is the point at which the particle rst begins to change shape or expand; the higher mperature is the point at which the maximum olume was reached. The range of sticking or adherg was determined by noting any tendency for the panded particles to adhere to the refractory clay mple plate upon which they rest during firing. In a tary kiln, the shale particles are constantly in conct with one another, and therefore they must pass t of the kiln before sticking develops. If the parcles stick to one another, they form large masses hich can be troublesome to remove from the kiln. ost of the samples tested had a temperature inrval of at least 50° F. between the point of maximum expansion and the point at which sticking began.

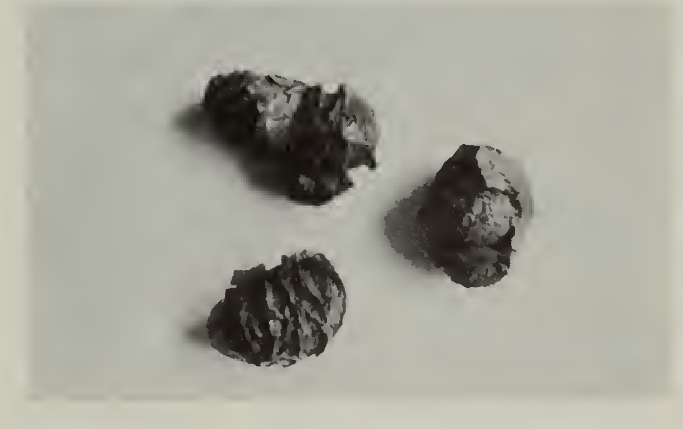
Spalling is the explosive shattering of shale particles during firing due to the rapid generation of gases within the particle, primarily from moisture. If spalling is not controlled, the shale will be reduced to a very small size regardless of the size fed into the kiln. The most common means of controlling this breakage is to dry the crude shale before it is introduced into the expanding kiln.

The shape of the expanded particle is determined by the degree of orientation of the clay minerals within the shale (photo 5). As was pointed out earlier, shale which has a slaty cleavage tends to expand only in the direction perpendicular to this cleavage so that an accordian-shaped particle results. Shale which does not display this cleavage expands equally in all directions to form a rounder particle.

The surface color of the fired aggregate will effect the color of the finished product in uses where the aggregate is exposed. Normally, the exact shade of color is less important than uniformity of color over a long period of production, allowing concrete blocks made from various batches of aggregate to be placed next to one another without a noticeable color difference. Nearly all of the samples tested produced the same brick-red surface color regardless of the origin or location of the sample. This color undoubtedly reflects the presence of ferric iron at the particle surface and samples which fire to a buff color (such as sample K-8 and K-15) probably have a low iron content.

All of the samples which expanded did so in a uniform manner which seems to be characteristic of the process of expansion. This uniformity suggests that the mechanism of expansion is the same in all of these samples regardless of their origin. The first observable effects of expansion take place at 1850° F. to 1900° F.,

Photo 5. Expanded shale particles. Two of the particles show accordian-like pleats which resulted from parallel orientation of the clay minerals in the shale (*Photo by Mary Hill*).



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pparent specific gravity is the ratio of the entire mass of the shale particle to the mass of water. The effect of closed pores within the particle is included in this term.

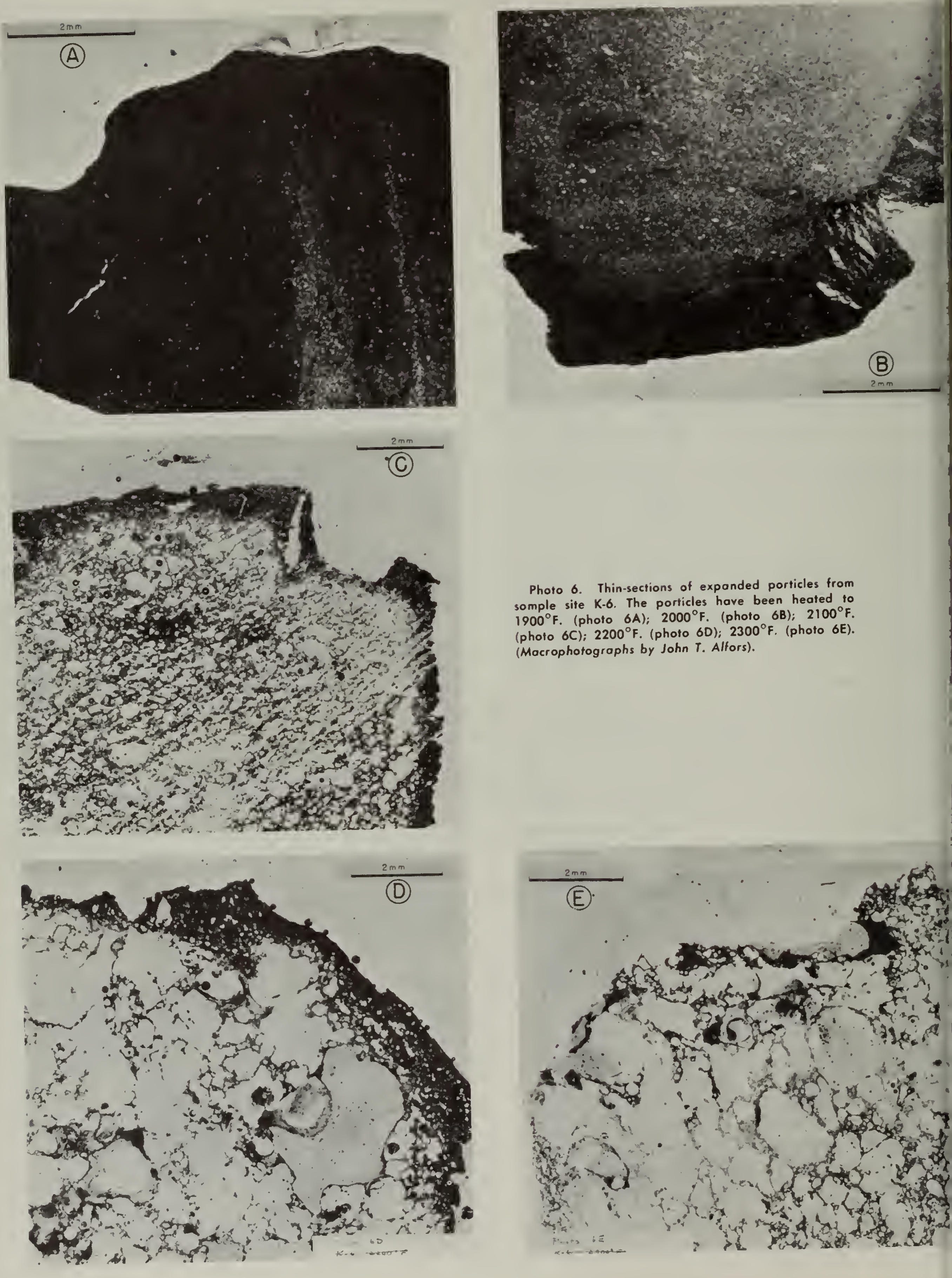

Photo 6. Thin-sections of expanded particles from sample site K-6. The particles have been heated to 1900°F. (photo 6A); 2000°F. (photo 6B); 2100°F. (photo 6C); 2200°F. (photo 6D); 2300°F. (photo 6E). *(Macrophotographs by John T. Alfors).*

en the surface of the shale particle begins to crack
l split open. At temperatures 25° F. to 50° F. above
s, the volume begins to enlarge as the outer shell of
particle bulges. When temperatures of 2000° F. to
00° F. are reached, the cracks in the outer shell are
ead apart and frothy glass begins to ooze from the
erior of the particle. As expansion continues, the
ginal outer shell is spread farther apart by enlarge-
nt of the central portion of the particle. During
s process, the particle surface is firm and not sticky,
ough the frothy glass which moved to the surface
viously had been melted in part when it was inside the
ticle. As the temperature continues to rise, the sur-
e begins to melt completely and sticking develops.
These observations indicate that melting take place
ially in the interior of the particle, but that this
lted portion solidifies when it reaches the surface
he particle. The outer shell, which is always in con-
with the atmosphere, may melt at a temperature
much as 200° F. above the melting point of the
rior. If the particle does not expand, the center of
particle does not melt until it reaches the higher
perature at which the outer shell also melts.

Vhen the particle is removed from the kiln, the
ace is black in color although this changes to
k-red when the particle is cooled. The red color
resent only in a thin outer shell that surrounds a
k grey interior of frothy glass. This red outer shell
borders cracks which penetrate the interior of the
icle from its surface, although the shell is not found
nd closed pores within the particle which do not
nect to the surface. These colors are significant
use they probably reflect the oxidation state of
within the glass. The dark grey interior of the
particle and the black color of the surface of
hot particle indicate the presence of ferrous iron
er these conditions. The red color of the cool
icle must, therefore, be strictly a surface effect
lting from atmospheric oxidation of iron to the
ic state during cooling.

hin-sections were prepared for study with the
ographic microscope from particles which were
l at 1900° F., 2000° F., 2100° F., 2200° F., and
° F. Brief descriptions of the features noted in
ble K-6 are presented below:

1900°F. (photo 6A).

No pores are noted. Many angular grains of detrital quartz and feldspar, which average 0.02 mm in size, are arranged in parallel bands of sedimentary origin. The brick-red outer shell is 0.2 to 2.0 mm thick and is separated from the black interior by a sharp but irregular line.

2000°F. (photo 6B).

Closed pores are well developed throughout the center of the particle and average 0.1 mm in diameter. The outer shell in dark reddish brown in color and is less uniform in thickness than before due to rupturing of the surface. The detrital mineral grains are uncorroded.

2100°F. (photo 6C).

The closed pores have enlarged to an average diameter of 0.4mm. The color of the outer shell is black in transmitted light although it is still reddish brown in reflected light. The outer shell averages only 0.4 mm in thickness and is extensively ruptured.

2200°F. (photo 6D)

The closed pores have greatly enlarged and range in size from 0.2 mm to 1.0 mm. Closed pores are present in the outer shell and average 0.1 mm in diameter. The color of the outer shell is still black in transmitted light but is reddish brown in reflected light. Many of the smaller detrital grains seem to have melted, and the larger detrital grains are greatly corroded.

2300°F. (photo 6E).

The closed pores have not greatly enlarged as compared to the 2200°F. specimen but many more small closed pores have formed. The walls between closed pores have become much thinner and suffered internal rupturing thereby joining adjacent pores. Most of the detrital grains have melted, although a few, small corroded grains are still visible. The outer shell is vesiculated with the exception of the outermost portion of the shell which averages 0.04 mm in thickness.

This study suggests that the large detrital grains remain as coherent crystalline solids until the final stages of expansion are reached and, therefore, they probably do not affect the process of expansion.

The firing behavior of these samples indicates one characteristic that may be of prime importance in explaining the process of expansion; this is the fact that the elements of expansion, namely low temperature melting and the formation of closed pores, initially take place in the interior of the particle and both are retarded upon contact with the atmosphere. The fact that the surface melts at a much higher temperature than the interior suggests that atmospheric oxygen—in the furnace atmosphere—is able to modify the melting point of the shale. In many cases, the factor which controls this difference in melting point may be the oxidation state of iron contained in the shale. It is well known that ferrous iron is a much more active flux at low temperatures than ferric iron. Although the color of the glass in reflected light indicates that considerable ferrous iron is present in the surface layer, enough ferric iron may form by reaction with atmospheric oxygen to elevate the melting point on the surface. This would explain the lack of stickiness and apparent solidification of the frothy glass when it moves to the surface of the particle. It is this difference in melting point which permits the rotary kiln method of expansion to function at all. The low temperature melting at the center of the particle provides enough viscous glass to promote expansion by trapping gases and the surface, which is more refractory, allows the particles to be in contact with one another in the kiln without sticking together.

A possible alternative explanation for this observed internal melting could be that the interior of the particle reaches a higher temperature than the sur-

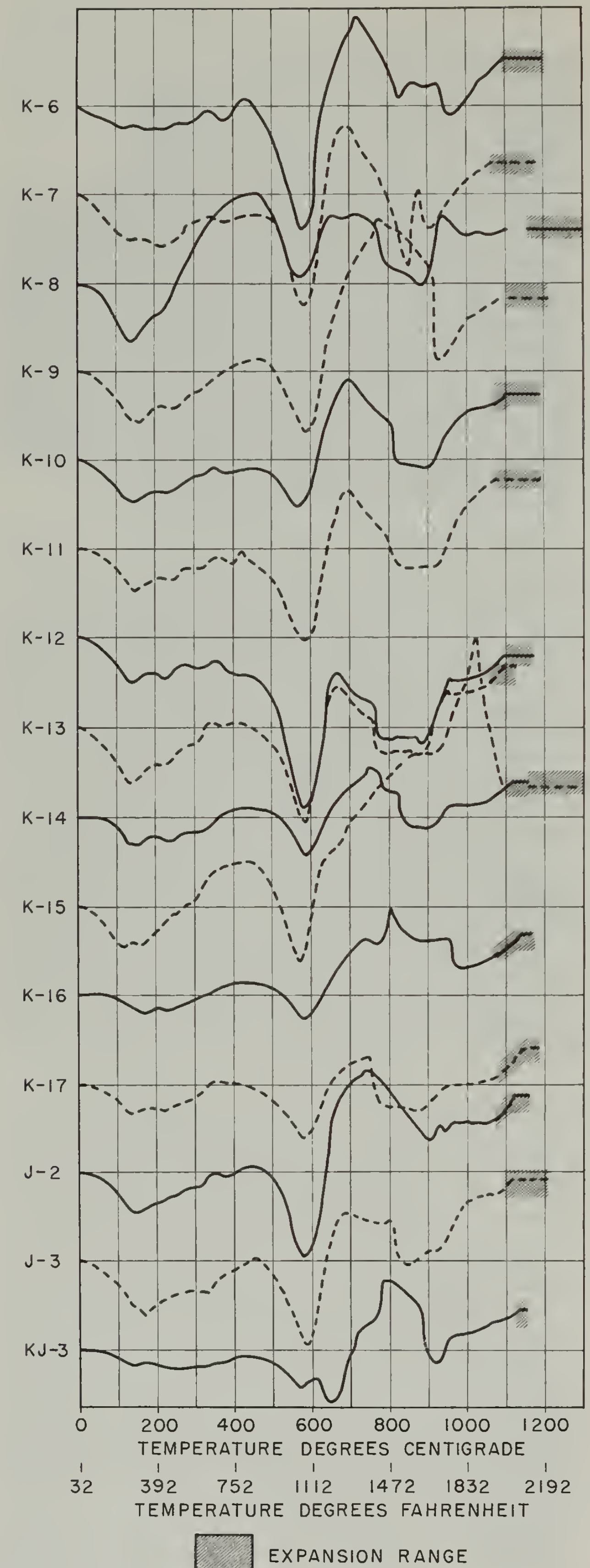

Figure 5. Differential thermal analyses of shale samples. R. M. Fulrath, analyst, Oct. 27, 1960.

face due to large-scale exothermic reactions with
the particle. If such reactions were solely respo
sible for the observed difference in melting poi
they would have to produce enough heat to rai
the interior temperature at least 100° F. and som
times 200° F. above that of the surface. The he
produced would be the sum of all thermal reactio
taking place within the particle at the temperatu
of expansion, rather than a specific reaction associat
with only one of the minerals present in the sha
For this reason, differential thermal analyses we
run on bulk samples of the shale rather than on a
separated fraction; the results are presented on figu
5 along with the temperature range of expansion,
reported on table 3. Although these curves gene
ally display a slight exothermic rise below the te
perature of expansion, there is no consistent gener
tion of heat on a large scale which would appreciab
increase the interior temperature of the shale partic

Chemical and Mineral Composition

The bulk chemical analyses of selected samples a
presented in table 4. The analyzed samples inclu
one from the Knoxville Formation (sample numb
J-2) and five others from scattered localities with
the Cretaceous (Berryessa Formation) shale.

The chemical constituents that were determin
fall into three generally recognized categories wi
regard to their effect on expansion. Silica (SiO_2) a
alumina (Al_2O_3) are refractory constituents whi
tend to raise the melting point of the shale. The flux
constituents which tend to promote low temperatu
melting, are represented in these samples by ferr
oxide (FeO) and to a lesser extent ferric oxi
(Fe_2O_3), lime (CaO), magnesia (MgO), pot
(K_2O), soda (Na_2O), titania (TiO_2) and phosphor
pentoxide (P_2O_5). Ferrous iron, lime, and magne
are the most effective fluxes at low temperatures
some combination of these constituents is probal
responsible for the partial melting that takes pl
when expansion begins. The remaining constitue
reported in table 4, water (H_2O), carbon diox
(CO_2), organic carbon (C) and sulfur triox
(SO_3), are the potential gas-producing constitue
of the shale.

Qualitative spectrochemical analyses were c
pleted on all samples which were collected for
study. The results, which are presented on tabl
have only qualitative significance because diffe
elements vary greatly in their sensitivity to detec
by this method. For example, phosphorous was
detected in the spectrochemical analysis althoug
is known to be present from the bulk chem
analyses (table 4). Conversely, many elements suc

Table 4. Chemical analyses of selected shale samples.
W. H. Herdsman, Analyst (July 27, 1961)

Sample number	K-6	K-10	K-13	K-14	K-17	J-2
O_2	59.93	63.33	58.28	58.46	56.91	57.58
$_2O_3$	17.76	16.23	16.82	17.03	17.40	16.23
O	5.09	2.16	2.66	.72	2.30	3.16
$_2O_3$	2.17	3.20	4.49	5.74	4.89	5.25
O_2	.74	.76	.76	.65	.69	.76
O	.56	.62	.78	.84	1.06	.62
gO	2.61	1.95	3.04	2.31	3.03	2.32
O	2.72	2.66	2.91	2.54	2.72	2.60
a_2O	1.54	1.94	1.46	1.54	1.74	1.46
O^+105°C*	5.86	6.47	8.14	8.99	8.57	8.20
O_2	.07	Nil	Nil	.03	.05	.13
	.61	.63	.57	.90	.46	1.24
O_5	.13	.13	.16	.13	.17	.16
O_3	.08	.09	.08	.09	.09	.09
	99.87	100.17	100.15	99.97	100.08	99.80

ater which was not removed by heating at 105°C.

Table 5. Qualitative spectrochemical analyses of shale samples.
John T. Alfors, analyst (June 23, 1960)

Elements detected	Sample numbers														
	K-6	K-7	K-8	K-9	K-10	K-11	K-12	K-13	K-14	K-15	K-16	K-17	J-2	J-3	KJ-2
	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	tr
	x	x	x	tr	tr	tr	tr	tr	x	tr	x	x	x	x	x
	tr	m	tr	tr	tr	tr	tr	tr	tr	tr	tr	m	tr	tr	m
	x	tr	x	x	x	x	x	x	tr	x	x	tr	x	tr	tr
	m	M	m	m	m	m	m	m	m	m	m	M	m	m	M
	tr	tr	x	x	x	x	x	x	tr	x	x	tr	tr	tr	tr
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	tr	m	m	m	m	m	tr	m	tr	tr	tr	tr	tr
	tr	tr	x	x	x	x	x	x	tr	x	x	tr	x	tr	tr
	M	M	M	M	M	M	M	M	M	m	m	M	M	M	M
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	x	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	tr	x	x	x	x	x	tr	x	x	tr	tr	tr	tr
	tr	tr	x	tr	tr	tr	tr	tr	tr	tr	x	tr	tr	tr	tr
	tr	tr	tr	x	x	x	x	x	tr	x	x	tr	tr	tr	tr
	m	m	tr	m	m	m	m	m	m	m	tr	m	tr	m	m
	tr	tr	tr	tr	tr	tr	tr	tr	tr	x	x	tr	tr	tr	tr
	M	M	M	M	M	M	M	M	M	m	m	M	M	M	M
	m	m	m	m	m	m	m	m	m	tr	tr	m	m	m	m
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	x	tr	tr	tr	tr
	tr	m	tr	m	m	m	m	m	tr	m	tr	m	tr	m	m
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	tr	tr	x	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	tr	x	x	x	x	x	tr	x	x	x	x	tr	tr
	x	x	x	tr	tr	tr	tr	tr	x	tr	x	x	x	x	x
	x	tr	tr	x	x	x	x	x	tr	x	x	tr	tr	tr	tr
	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	x	x	x	tr	tr	tr	tr	tr	x	tr	x	x	x	x	tr
	tr	m	m	m	m	m	m	m	m	m	tr	m	tr	m	m
	tr	tr	x	tr	tr	tr	tr	tr	x	tr	tr	tr	tr	tr	tr
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	m
	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	tr	tr	x	tr	tr	tr	tr	tr	tr	x	x	x	tr	tr	tr
	x	x	x	tr	tr	tr	tr	tr	x	tr	x	x	x	x	x

onstituent probably major.
onstituent probably minor.
tr—Constituent probably trace.
x—Not detected.

Table 6. Crystalline content of shale samples by the X-ray diffraction method.

R. B. Langston, Analyst (June 28, 1961)

Crystal form	Quartz	Feldspar	Mica	Disorganized Kaolin	Vermiculite	Chlorite
Spacing of line in angstrom units (Å)	3.34	3.20	10	7.1	14	14
Sample No.	Intensity of indicated spacing in counts per second					
K-6	176	28	14	--	--	17
K-7	180	36	20	--	--	34
K-8	288	12	--	--	--	--
K-10	220	48	12	Tr	--	--
K-11	224	32	8	Tr	4	-
K-12	200	44	10	10	8	--
K-13	200	48	8	20	--	--
K-14	220	60	12	16	18	--
K-15	230	44	10	--	Tr	--
K-16	172	40	24	20	32	--
K-17	144	36	24	36	20	--
KJ-2	150	32	68	60	16	--
J-2	160	24	12	20	8	--
J-3	180	48	12	..	16	--
Standard (40 percent quartz, 60 percent feldspar)	288	96	--	--	--	--

gallium (Ga) and praseodymium (Pr) are reported in all samples although they may constitute less than 0.01 percent of the sample.

The spectrochemical analyses provide some information on the composition of those samples which were not analyzed by wet chemical means. The results suggest that all of the samples contain the same major constituents although the concentration of these constituents cannot be determined. The spectrochemical analyses also provide information on the content of trace elements and other constituents for which specific analyses were not attempted by the wet chemical method. Manganese (Mn) is a minor constituent in most of the samples and barium (Ba) and copper (Cu) appear to be present as minor constituents in several of the samples. All of the samples contain nearly the same trace elements with the exception of the single sample from the Franciscan Formation (KJ-2), which differs from the others in containing traces of arsenic (As) and a higher vanadium (V) content.

The mineralogy of the shale samples was examined by the X-ray diffraction method[*] and the data obtained from this study are presented in table 6. The results are reported in terms of the diffracted intensity of one of the characteristic spacings used to identify the mineral and, although this information cannot be directly related to the percentage of the mineral present, it can be used for approximation. Diffraction data on a quartz-feldspar standard hav been included on table 6 so that the quartz and feldspar content may be estimated more accurately. Th identity of the other constituents was verified b the effect on the characteristic diffraction spacin when separate portions of the sample are drie treated with ethylene glycol and fired at 420° C. an 600° C.

The shale samples were found to contain as muc as 25 percent of poorly crystallized or amorpho clay. Quartz and feldspar may total 65 to 75 pe cent of each sample; approximately equal amoun of each are present in most of the samples. The clay size fraction was concentrated by using a sediment tion technique similar to that used in the Andrease particle size determination test (Loomis, 1938). A though a clean separation of the clay-size fractio was not obtained, that fraction of the samples whic was smaller than six microns seemed to be about to 20 percent. The minerals that were concentrate in the clay-size fraction were mica, a poorly crysta lized kaolin mineral, vermiculte, and chlorite. Th mica, which probably should be classified as a bioti because of its low thermal stability, is most abunda Hydromica, or illite, was not identified in any of t samples.

It was previously noted that the expansibility these samples is, in many cases, associated with t color of the shale; samples in which shades of bla and dark green predominate tend to expand the mo hese colors usually indicate the presence of organic irbon and ferrous iron (Weller 1960) and these onstituents have, in other investigations (Herold al., 1958, Conley, et al., 1948), been thought to lay an important role in the process of expansion. i the present study, a semi-quantitative technique of ialysis was used to estimate the content of these conituents (Appendix B); the results of this test are ported in table 3 as reducing power. The technique based on the reduction of potassium dichromate by ganic carbon and, to a lesser extent, ferrous iron; it similar to a method described by Allison (1935). he sample is ground and standardized quantities of iale and potassium dichromate are digested in conntrated sulfuric acid. The potassium dichromate is duced in proportion to the quantity of readily atcked reducing agents present in the shale. The maining potassium dichromate is determined by rating with ferrous ammonium sulfate using diienylamine as an indicator. The amount of potasim dichromate expended by reduction is determined difference between the amount remaining and ie amount originally used.

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[*] This section is condensed from an office report by R. B. Langston, Department of Mineral Technology, University of California, Berkeley (June 28, 1961).

The quantitative significance of this technique is nited because both organic carbon and ferrous iron ill react with the potassium dichromate, but the tal content of these reducing agents does not necesily react under the conditions of the test. By comring the carbon content (table 4) and the reducing wer (table 3) of the six samples which were chemilly analyzed, it can be seen that these two propies increase together in most samples. The exceptons to this correlation are samples in which the rbon content was low but the reducing power was gh; this may have been caused by the reaction of rous iron which was present in pyrite or the silite minerals. No sample had both a high carbon ntent and a low reducing power, which suggests at a fairly uniform percentage of the total carbon reacting under the conditions of the test.

The reducing power of these samples does not actly correlate with the degree of expansion, but e best expanders tend to have a high reducing wer. The test results are probably a good indicaon of the amount of weathering that the sample s suffered, because both organic carbon and ferrous on are readily oxidized during weathering. One mple (K-15) had an extremely high reducing power d yet it expanded very poorly. White (1960 p. 5) und that expansion may be inhibited by large quanies of carbon (more than 2 percent) in the shale. his may be the reason for the poor expansion of is sample, although its buff-white fired color indites that it is also deficient in iron.

Other Measurements

The pH of a shale-water slurry was determined, for each of the samples studied (Appendix B). Conley, et al. (1948) reported a correlation between the pH and the expansion of shale; expansible shales tend to have a pH above 5 while those which do not expand tend to have a pH below 5.

In the present investigation it was found that the best expanders tend to have a high pH but that no pH value could be used as an index of expansion. The best and the poorest expanders had the highest and the lowest pH values respectively, but between these extremes many samples with similar pH values displayed very different degrees of expansion.

Water absorption of the expanded aggregate was determined using a test adapted from California Division of Highways test method 206-B (Appendix B).

The water absorption tends to be higher in those samples which have expanded the most. For a given degree of expansion, those samples which produced an accordion-shaped particle absorb more water than samples which expanded to a round shape. It has been pointed out above that accordion-shaped particles result from the slaty cleavage which is developed in some shales. Therefore, slaty shale may be expected to produce aggregate with higher water absorption than do non-slaty varieties.

Review of the Literature

Expansion is a physical effect which is controlled by the chemical and physical properties of the raw material. There is agreement on the general conditions leading to expansion but the existing literature contains a wide variety of conclusions regarding the specific causes and criteria of expansion. The factors which are most commonly considered to be of importance are the effect of bulk chemical composition and mineral composition on melting, the origin of the gases which cause vesiculation, and the retention of these gases within the shale particle.

In his work on Minnesota clays and shales, Riley (1951) defined a range of chemical compositions which he considered to be necessary for expansion to take place. The chemical composition controls the viscosity of the melt produced during firing and this, he felt, was of critical importance. Other workers have criticized the specific details in this study (Harold et al., 1958, p. 25), but there is general agreement that the refractory and fluxing agents must be balanced in such a way as to result in a glass at low temperatures which is viscous enough to retain the gases as they expand. Many workers point out that the composition of a non-expanding shale can be adjusted by the use of additives in order to induce expansion (Conley, et al., 1948, p. 10; Riley, 1951, p. 123; Herold et al., 1958, pp. 20–27).

The effect of mineral composition has been investigated in most of the studies conducted in recent years. Plummer and Hladik (1951, p. 19), working in Kansas, state that illitic shales usually bloat at high temperatures; kaolinitic clays do not bloat except by overfiring; and that montmorillonitic clays bloat to a low density material with gas vesicles almost microscopic in size. Everhart (1959) states that the ratio of illite to kaolinite is of prime importance in the expansion of Ohio clay and shale. Mielenz and King (1955, p. 246) state that the most promising sources of lightweight aggregate are shales and clays containing illite, beidellite-type members of the montmorillonite group, and vermiculite-chlorite. Other workers have concluded that there is little or no correlation between the mineralogical composition and the expansion of a sample (Conley et al., 1948, p. 9; White, 1960, p. 4). W. F. Cole (1960) points out that the ceramic behavior of a clay in an industrial process is often controlled by factors other than clay mineralogy, and questions the practical value of mineralogical studies.

The origin of the gases which cause vesiculation and subsequent expansion has been investigated more thoroughly than any other phase of the process of expansion. These gases are usually considered to originate through the thermal destruction of certain minerals, with the creation of a gas phase plus new compounds which are stable at higher temperatures. Conley et al., (1948) discussed the role of carbon and hydrocarbons, carbonates, sulfates, sulfides and the thermal dissociation of ferric oxide. Riley (1951) emphasized the importance of ferric oxide and Ehlers (1958) considered the generation of CO_2 from carbonates to be of prime importance in clay and shale from Ohio. White (1960), working in Illinois, reported that organic carbon must be present within certain limits in order for expansion to take place, and noted that surficial weathering would commonly remove enough carbon to prevent expansion.

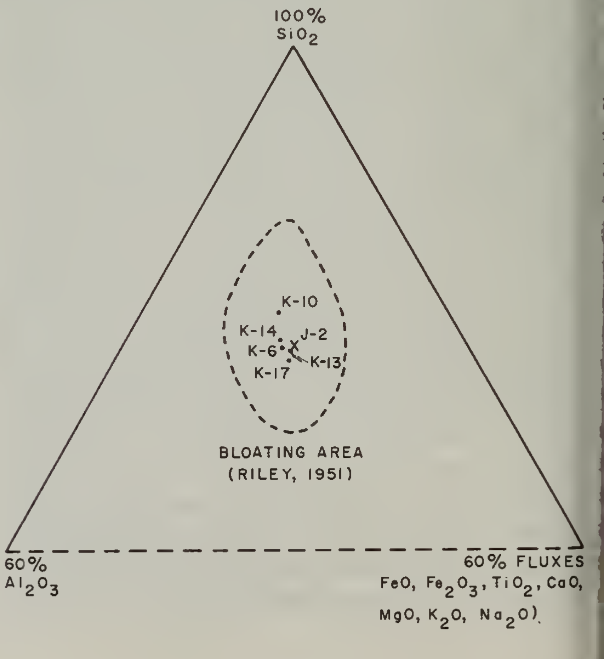
In an unpublished paper, Doolittle (1954) found a correlation between the mol ratio of carbon and ferric oxide in the crude shale and the carbon remaining after burning; he concluded that the main gas-forming reaction was reduction of ferric oxide by carbon.

Retention of the gases within the shale particle is controlled by the fabric of the rock and the distribution of particle sizes. Conley et al., (1948, p. 17) believe that carbon probably burns out of loose granular clay before bloating temperatures are reached, thereby inhibiting expansion. They also note (p. 72) that in all samples of slate tested, expansio occurred largely in a direction normal to the cleavag or stratification planes of the material. Mielenz an King (1955, p. 245) report that the fabric of the shal is significant in the expansion process; the most beneficial is a dense, relatively impervious fabric whic resists shrinkage during heating and retards releas of vapors and gases before fusion effects a seal i the particles. Murray and Smith (1958, p. 29) foun no apparent correlation between the bloating characteristics of Indiana shales and the amount of sanc silt, and clay which they contained. Their study suggested that fabric is more important than difference in size gradation, especially when the size range fal within the silt and clay size. White (1960, p. 28 reported that the expansion of Illinois shales take place normal to the bedding and that (1959, p. 2) we laminated shales tend to expand better than poorl laminated shales and clays.

Discussion

The samples investigated from the San Jose-Gilro area have many similarities to materials which hav been studied in other areas, but the divergence o opinion as to the precise causes of expansion ind cates that the data collected and conclusions draw from one material are not applicable to other m terials. This is not surprising when one remembe that expansion results from a critical balance betwee the melting of a complex multi-component chemic system and the generation and retention of at lea one, but probably more than one, gas from some pa

Figure 6. Compositional diagram of analyzed shale samples. T dashed line indicates the limits of the "bloating area" as defined Riley (1951).



this system. Most of the investigations that have n carried out to date have used indirect methods study, due to the extreme difficulty of directly isuring and observing reactions at high tempera- es.

'he six analyzed samples in the present study similar to materials which have been studied in er investigations. When the analytical results of e 4 are plotted on a compositional diagram (figure the points all lie near the center of the bloating , as defined by Riley (1951). Although the bulk nposition was not determined for nine of the ples collected for this study, their firing behavior lting point, fired color, expansion properties) gests that most of them have a bulk composition ch is suitable for expansion. Sample numbers and K-15 fired to a pale buff color, which indi- d that they contain less iron than the other ples. Inasmuch as the sample localities were dis- uted along 40 miles of the exposed Cretaceous ks east of San Jose and Gilroy, the bulk chemical nposition of the shale within this entire unit should close to that required for proper expansion.

he mineral composition of these samples is charac- ted by poorly developed crystallinity within all he minerals and the presence of rather large ntities of amorphous material. No member of the tmorillonite or illite groups were recognized in sample. Quartz and feldspar are abundant in the -size range although they are more common in material coarser than this size.

here is a wide divergence of opinion as to the t of the clay minerals on expansion. It seems rea- ble to the writer that mineralogy is important to the extent that it controls grain size and nical composition. There is no reason to believe the atomic structure of the mineral, which is the ure detected by the X-ray diffraction method, tributes to expansion, especially as this structure is ely destroyed in the temperature range where nsion takes place. Kaolinite is commonly cited non-expansible constituent. The reason for this bably lies in the fact that pure kaolinite consists ydrated silica and alumina, and melting takes e far above the normal temperature of expan- . When kaolinite is mixed with large quantities other minerals containing fluxes, expansion can place (Everhart, 1959). On the other hand, clay erals of the montmorillonite group are often con- red to be conducive to expansion. The crystal e of these minerals contains sites for fluxing con- ents (sodium, magnesium, iron etc.) as well as refractories, silica and alumina. In addition, there om between the lattice layers for a wide variety of exchangeable cations which can contribute to fluxing. Another factor, which bears on gas retention, is that the individual crystals of the montmorillonite clays are extremely small and this ultrafine grainsize would promote impermeability during firing. Plummer and Hladik (1951, p. 19) noted that montmorillonite clays expand to a low density material with closed pores almost microscopic in size; the same is true of commercial aggregates which are produced in California from montmorillonite-rich clays. This small pore size indicates that gases are not only retained by the surface of the particle but that the fine grain size of the clay seals the individual points of gas expansion within the interior of the particle from one another.

The minerals in the samples investigated for this study are so poorly crystallized that only quartz and feldspar can be identified with certainty. Even so, the bulk chemical composition is suitable for proper melting, and enough fine-grained material is present for proper gas retention. Regardless of the mineral composition, if these two conditions are established, expansion is possible.

The gases which cause expansion in these samples were not directly investigated, but some information on their identity and origin can be inferred from the analytical data collected. It has been mentioned that the state of reduction of the shale, as reflected in the reducing power and color of the rock, tends to correlate with expansion. It has also been pointed out in this and other studies that surficial weathering can readily reduce or eliminate expansion. Although both ferrous iron and organic carbon are readily oxidized, weathering should more effectively remove organic carbon, which is normally present as a grain coating, than ferrous iron, which is normally locked in a protective mineral framework. The test for reducing power used in this study was originally proposed (Allison, 1935) as a quantitative test for organic carbon and, although ferrous iron interferes with the test, there can be little doubt that the results primarily reflect the content of organic carbon. It is unlikely that weathering has sufficiently changed the bulk chemical composition or permeability of these samples to affect expansion. Carbon dioxide from carbonate minerals and sulfur trioxide from sulfate minerals can be responsible for expansion, but the chemical analyses of these shales (table 4) indicate so small a quantity of these constituents that their effect on expansion should be slight. All of these factors combine to suggest that the content of organic carbon is critical in the expansion of shale from this area.

Many previous workers have suggested that organic carbon contributes to expansion by reducing ferric iron and forming either carbon monoxide or carbon dioxide gas. The probable reactions in unbalanced form are as follows:

$$Fe_2O_3 \rightarrow FeFe_2O_4 + O_2$$
$$C + O_2 \rightarrow CO_2 \pm CO$$

These reactions require iron in the ferric state of oxidation. White (1960, p. 11) suggests that some of the original ferrous iron present is oxidized to the ferric state by oxygen derived from hydroxyl groups within the clay mineral structure. The ferrous iron produced by the former reaction is a powerful flux at relatively low temperatures (Searle and Grimshaw, 1959. pp. 280–281) and would contribute to fusion of the shale particle. One apparent anomaly is that the reduction of ferric iron alone will produce the essentials for expansion: oxygen as a gas phase; and ferrous iron which would act as a low temperature flux. Ferrous oxide is more stable than ferric oxide at high temperatures, and reduction can solely a thermal effect without the need of a reduc agent such as organic carbon. The black surface co of the hot particles as they are removed from kiln indicates that ferrous iron is stable even in highly oxidizing atmosphere of the electric k There would seem to be no necessity for organic c bon, and yet this constituent seems to be essent The explanation for this may lie in the solubility oxygen in the liquid phase (glass) being form Oxygen and other gases such as water vapor hydrogen are able to escape from closed pores vitreous bodies by solution and diffusion while car monoxide and carbon dioxide cannot because of t low solubility in the liquid phase (Kingery, 1960, 393). It may be that organic carbon is not necess to form a gas phase but is essential in that it combi with oxygen to form a gas which has low solubil in the liquid phase. This would allow the gas develop enough vapor pressure within the clo pores to enlarge them.

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APPENDIX A

Sample Locations

6 (Sec. 18, T. 9 S., R 4 E., MDB)

The sample site is located in a steep stream gorge, 200 yards north
the north abutment of Cachrone Bridge, 20 yards northeast of the
ad. This is the most completely exposed section found in the area.
e steep slope rising above the site is the scarp of the Calaveras
ult. The bedding is deformed but generally dips to the east at a
derate angle.

The shale is a black, well bedded, well indurated material which lies
tween massive, well indurated beds of sandstone. The stratigraphic
ckness exposed is approximately 120 feet. The site contains about 50
rcent of slightly sandy shale. Calcite occurs as thin (⅛ to ½ inch)
erbeds which are separated by 5 to 10 feet of shale. Thin (⅛ to ½
h), crosscutting veins of secondary calcite are irregularly distributed
ough the shale; they are generally no more common than the inter-
ds. The calcite interbeds and veins make up less than ½ percent of
total exposed material.

The sample site would not be desirable for commercial development due
its proximity to Anderson reservoir and the steepness of the topog-
hy, but similar rocks should be found in the tributary canyons to
northwest.

7 (Sec. 12, T. 9 S., R. 3 E., MDB)

he sample site is located in a small quarry opening on Steeley Road
feet up from a hairpin curve. The shale is black, well bedded and
ll indurated, with a prominent conchoidal fracture. No sandstone is
ble in the exposure. Some thin films of secondary calcite were noted.
his sample displayed the highest degree of expansion of any in the
up.

(Sec. 4, T. 9 S., R. 4 E., MDB)

he sample site is located in a road-cut on a private road connecting
doza Ridge with Steeley Road.

he shale is dark brown, well-bedded and moderately indurated. No
dstone or limestone seams are exposed. Veinlets of limonite were
ed. The shale appears to be slightly weathered.

he sample expanded very well but only at rather high temperatures.
pale buff color of the fired material indicates a deficiency in iron.

(Sec. 34 projected, T. 8 S., R. 3 E., MDB)

he sample site is located in a shallow road cut on a private road
nile northwest of Lone (Lost) Lake.

he shale is dark green, moderately well bedded, well indurated with
derately developed conchoidal fracture.

oose fragments of sandstone are common along the side of the
d but only a small quantity was found in place. No limestone was
ed.

he sample is slightly weathered, which may account for its moderate
ree of expansion.

0 (Sec. 22 projected, T. 8 S., R. 3 E., MDB)

he sample site is a roadcut on a private road which connects San
pe Creek with Carlin Canyan, 150 yards north of a water tank on
Felipe Creek.

he shale is dark green and massive. Sandstone makes up 30 per-
of the material exposed. No limestone was noted.

1 (Sec. 21, T. 8 S., R 3 E., MDB)

he sample site is a roadcut at the junction of two private roads; one
e road along San Felipe Creek and the other connects this road
Las Animas Creek.

he shale is blackish-green and moderately well bedded. Sandstone
limestone are not visible, although some sandy shale is present.

2 (Sec. 11, T. 10 S., R. 4 E., MDB)

he sample site is a roadcut along Gilroy Hot Springs Road.

he shale is dark green, hard and compact.

any out-of-place limestone nodules were noted in this general vi-
y. Nodule samples 1, 2, and 3, were collected within a mile of
site.

3 (Sec. 12, T. 10 S., R. 4 E., MDB)

he site is a roadcut in Gilroy Hot Springs Road, ¼ mile west of its
tion with Canada Road.

The shale is dark green, well bedded, and well indurated. Massive sandstone overlies the shale; the lower contact of the shale is not exposed. The sample was taken approximately 20 feet stratigraphically below the sandstone. The total exposure of shale, some of which is sandy, is over 200 feet thick. Several small limestone nodules were noted in place.

The sample expanded very well at a relatively low temperature (2050°F.).

K-14 (Sec. 36, T. 9 S., R 4 E., MDB)

The sample site is a roadcut on a private road which passes along the crest of Palassou Ridge. The location is immediately south of a small reservoir near the boundary between sections 35 and 36.

The shale is brownish green and appears to be considerably weathered. Conchoidal fracture is well developed. Some interbedded sandstone is visible in the roadcut.

K-15 (Sec. 17 projected, T. 11 S., R. 5 E., MDB)

The sample was taken from a small body of shale which is exposed in a roadcut along State Highway 152, about 1½ miles northwest of the town of San Felipe.

The shale is black, massive, well indurated and is cut by numerous seams of limonitic clay. Conchoidal fracture is well developed. The exposure is approximately 100 feet wide and is bounded on both sides by sandstone.

The sample did not expand. This may be due to an excessively high carbon content, as indicated by the high reducing power of the sample, or a deficiency of iron, as indicated by the buff-white color of the fired aggregate.

K-16 (Sec. 11, T. 5 S., R. 1 E., MDB)

The sample site is a roadcut in Calaveras Road, ¼ mile north of its junction with the road leading to Calaveras Dam.

The shale is dark green, well bedded, well indurated and slightly silty. Conchoidal fracture is moderately developed.

K-17 (Sec. 3, T. 5. S., R. 1 E., MDB)

The sample site is a roadcut in Calaveras Road, 300 yards south of the junction of this road and one along Alameda Creek.

The shale is dark green, well bedded, and moderately well indurated. No sandstone is visible. Several large (6 to 8 inches) limestone nodules were found in place. Nodule sample 4 was taken from this site.

J-2 (Sec. 2 projected, T. 8 S., R. 2 E., MDB)

The sample site is a roadcut in San Felipe Road, 100 yards east of an overhead power line.

The shale is black, well bedded, moderately well indurated, and somewhat altered and sheared along the bedding planes. There are some limestone interbeds which are black, massive, and well bedded. These interbeds are discontinuous and reach a maximum thickness of 1 inch to 3 inches. A few sandstone beds are visible but they are not common.

This sample expanded very well at a relatively low temperature and produced an accordion-shaped particle. This sample had the highest water absorption of any in the group.

J-3 (Sec. 7, T. 8 S., R. 3 E., MDB)

The sample site is a roadcut on the road leading to San Felipe Valley; it is located 200 yards north of Highland School. The bedding is moderately contorted.

The shale is dark green and moderately weathered. No sandstone or limestone is visible. The relatively low degree of expansion displayed by this sample is probably due to weathering.

KJ-2 Unsurveyed land. The site is located where the eastern border of the U.S. Geological Survey Pacheco Peak 7½ minute quadrangle crosses State Highway 152.

The sample was taken from a small body of slaty shale which is exposed in a roadcut on State Highway 152.

The shale is dark grey and has a well developed slaty cleavage. The bedding is extensively contorted.

The sample expanded well to produce an accordion-shaped particle.

APPENDIX B

Testing Procedures Used

Reducing Power Determination

Crush the sample in a non-ferrous mortar to pass a 60 mesh screen. Weigh out exactly 100 mg. of sample, and place in an Erlenmeyer flask. Add exactly 10 ml of 0.01 N potassium dichromate by pipet. Add 10 ml of concentrated sulfuric acid. Swirl the solution in the bottom of the flask to mix the solution during digestion. Heat is supplied by hydration of the sulfuric acid. After one minute, cool the flask by running cold water over its exterior. Add approximately 100 ml of distilled water and 5 g. of sodium fluoride powder (1 level teaspoon). Cool the flask again under running water. Add approximately 50 ml of distilled water, washing down the walls of the flask. Add three drops of diphenylamine indicator. Titrate with 0.1 N ferrous ammonium sulfate solution. Color change at the end point is muddy brown ——> slate blue (end point) ——> blue green. The reaction used during titration is:

$$Cr_2O_7^{--} + 6\,Fe^{++} + 14\,H^{+} = 6\,Fe^{+++} + 2Cr^{+++} + 7H_2O$$

The concentration of the potassium dichromate solution must be carefully standardized for the results to be comparable, but the ferrous ammonium sulfate may be mixed approximately and standardized against the potassium dichromate by using a blank run without sample. The potassium dichromate expended by a sample may be calculated from the following (all units are in ml):

$$\begin{matrix}K_2Cr_2O_7\\ \text{expended}\end{matrix} = \begin{matrix}\text{Total}\\ K_2Cr_2O_7\\ \text{added}\end{matrix} - \frac{\begin{matrix}\text{Total}\\ K_2Cr_2O_7\\ \text{added}\end{matrix} \times \begin{matrix}\text{ferrous ammonium}\\ \text{sulfate expended}\end{matrix}}{\begin{matrix}\text{ferrous ammonium sulfate}\\ \text{expended in a blank run}\end{matrix}}$$

With the quantities used in the procedure stated above, the formula reduces to the following:

$$\begin{matrix}K_2Cr_2O_7\\ \text{expended}\end{matrix} = 10 - \frac{10 \times \begin{matrix}\text{ferrous ammonium}\\ \text{sulfate expended}\end{matrix}}{\begin{matrix}\text{ferrous ammonium sulfate}\\ \text{expended in a blank run}\end{matrix}}$$

Determination of the Apparent Specific Gravity and Water Absorption of the Fired Aggregate

The method is adopted from California Division of Highways method 206-B (January 3, 1956). Approximately 30 particles of agg gate were used in each determination.

The sample was soaked in water for 20 hours, and then weig under water by suspending a basket from a beam balance. If particles tended to float, they were submerged by using a metal co on a basket and suitable tare weights were used to balance the be The samples were removed, patted with a towel to remove surf water and immediately weighed in air. The samples were dried for hours at 280° F., cooled and weighed again in air. The values w calculated from the following formulae:

$$\text{Apparent specific gravity} = \frac{\text{dry weight}}{\text{dry weight} - \text{weight in water}}$$

$$\text{Percentage water absorption} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100$$

Determination of pH

The sample was ground to pass a 60 mesh screen. Approxima 200 mg of sample and 2 ml of distilled water were placed in a gl beaker and stirred to insure thorough wetting of the sample. A Beck Model DU pH meter was used to measure pH after allowing seve minutes for the electrodes to reach equilibrium in the suspension.

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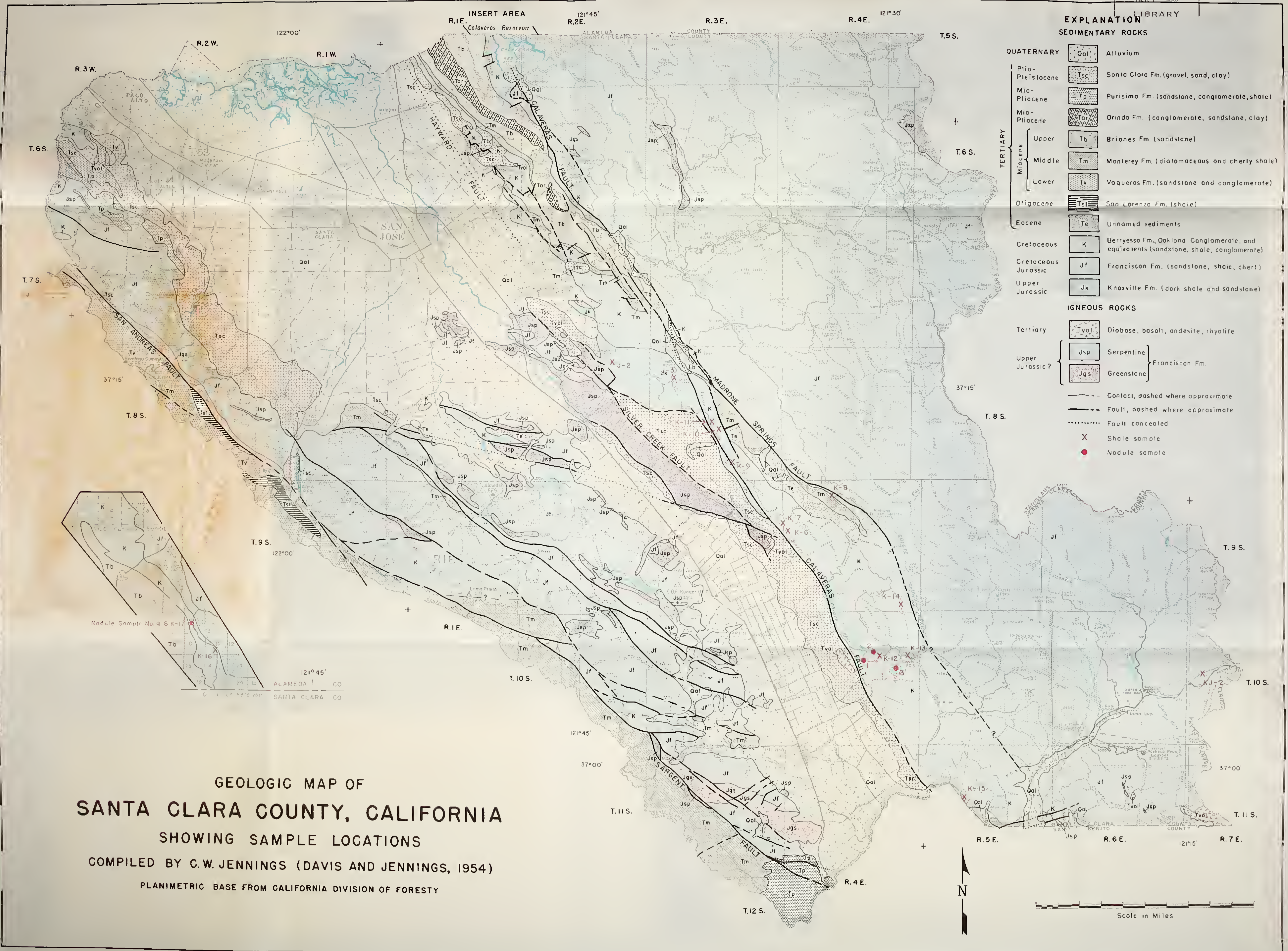

GEOLOGIC MAP OF
SANTA CLARA COUNTY, CALIFORNIA
SHOWING SAMPLE LOCATIONS

COMPILED BY C. W. JENNINGS (DAVIS AND JENNINGS, 1954)

PLANIMETRIC BASE FROM CALIFORNIA DIVISION OF FORESTY